Effectiveness of Personal Protective Equipment (PPE) for Use in Demining AP Landmines

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ABSTRACT

To reduce human casualties associated with demining, a wide range of protective wear has been designed to shield against accidental detonation of the AP landmines. Injury protection offered by personal protective equipment (PPE) may include, but is not limited to, head/face protection and thorax protection that may offer the potential for substantial defense against fragments, blunt force trauma, burns, and other consequences of mine blasts. In this study, five commercially available PPEs were evaluated. These suits represent a wide range of materials, masses and areas of head, neck, thorax and extremity coverage available.

This study utilized the Hybrid III dummy, an instrumented biofidelic surrogate that is anthropometrically similar to the human body. The primary dummy was a 50th percentile male, anthropometrically scaled to the average North American adult male. Tests were conducted with both an unprotected dummy and a dummy clothed with one of the five commercially available PPEs. Based on recorded dummy values, injury risk assessments were made using human or animal injury models. The PPEs were evaluated against two levels of simulated mines containing 100 g and 200 g of C-4 explosive, and a widely fielded antipersonnel mine, the PMN which contains 240 g of TNT. The test matrix consisted of 102 tests to confirm repeatability and robustness of the dummies, as well as to evaluate the five PPEs, two size dummies, and two positions (kneeling and prone).

The goal of this study was to determine the level of protections offered to the head, neck and thorax by the protective equipment. Correlations were drawn between injury risk and various parameters such as PPE mass, projected area, and dummy coverage area. The effect of certain PPE design features was significant. For example, higher mass PPE helmets resulted in lower head accelerations and lower neck moments. This was due to the increased inertia of the dummy by the added mass of the protective equipment. However, those PPE that presented a larger projected frontal area to the blast wave resulted in higher total momentum transfer, increased peak load, moment and acceleration. Two of the PPE that were evaluated did not include a helmet. The lack of helmet reduces the projected area and thus the loading area, but significantly increased the risk of injury by reducing the head/neck inertia and increased susceptibility to fragments and blunt trauma.

1. INTRODUCTION

This study reports the results from comparative testing of 5 Personal Protective Equipment (PPE) using a test methodology developed to evaluate the risk of injury from blunt trauma from the explosion of an anti-personnel (AP) land mine. It is based on a test methodology reported in Bass et al [Bass-2001] using an implementation of a test fixture developed under a US/Canada collaborative program [Nerenberg-2001, Chichester-2000] shown in Figure 1. Essential elements in this test methodology are:

- Repeatable, quantifiable threat (mine) – with fixed burial and soil characteristics.
- Robust dummy surrogate with established and applicable injury criteria – positioned in a realistic manner in positions representative of demining (i.e. kneeling and prone).
- Accurate positioning – distance to mine must be consistent and quantifiable.
- Robust instrumentation – data handling consistent with the response.
- Reasonable threat level, to identify the level of protection.

Each of these elements contribute to the overall objectivity of the methodology so that existing injury criteria may be used to assess PPE performance while ensuring that the resulting criteria are as applicable as possible to the conditions experienced in the real world

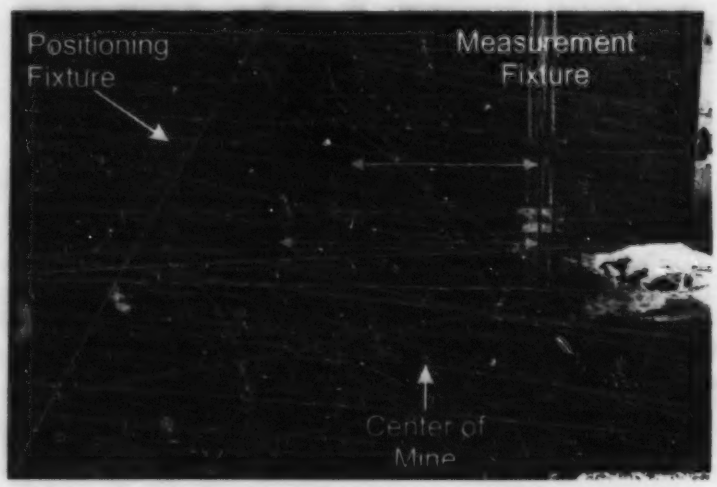

Figure 1: Kneeling Dummy with Positioning and Measuring Fixtures.
(Note: positioning fixture not used for the prone position)

The tests were performed using simulated mines containing 100 g and 200 g of C-4 explosive, and a PMN mine containing 240 g of TNT. The dummy used was a Hybrid III 50-th percentile male dummy, commonly used for blunt impact studies in the automobile industry. Sensors in the head, thorax, and chest were used to determine the injury risk from blunt trauma, and the distance to the mine was chosen to allow the discrimination of injury risk to a deminer while wearing PPE.

2. TEST SETUP

The test dummies were positioned in two common demining positions, kneeling and prone [Bass-2001], as depicted in Figure 2. The distance from the nose of the dummy to the center of the mine was 70 cm for the kneeling position and 45 cm for the prone position. Both the kneeling and the prone positions were selected to establish a baseline position that was severe enough to produce a significant risk of injury in the unprotected dummy, but not too severe that the dummy could be damaged or that the most protective of the PPEs could not reduce the injury criteria values. *As the blast has a conical streaming flow, the kneeling position often results in greater mine blast loading than the prone position* [Bergeron-2000, Bass-2001].

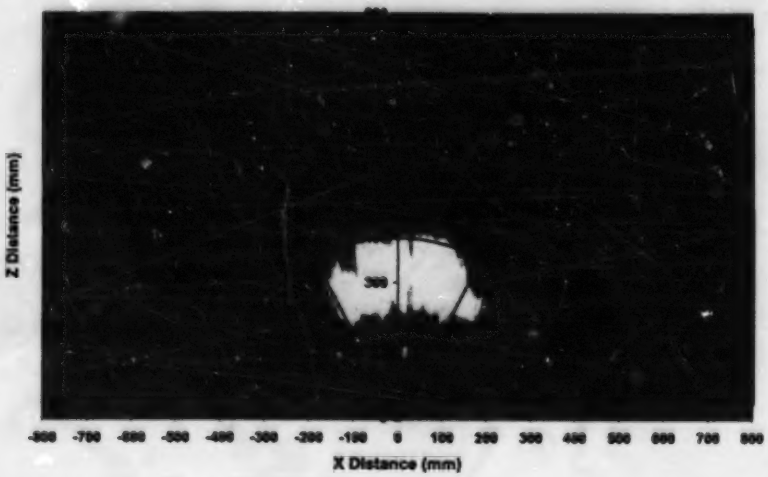

Figure 2: Nominal Kneeling and Prone Positions Relative to the Center of the Mine, radial Lines at 30^0 and 60^0.

Test Matrix

The tests reported in this study were designed to investigate the effectiveness of the PPE in protecting against blunt trauma from mine blast. Five styles of PPE suits were tested against two simulated mines and one actual mine. These suits were identified as PPE 1 – PPE 5 as shown in Figure 3 - Figure 7. Baseline tests were performed on unprotected dummies for each position and each of the simulated mines. The same tests were then repeated with the dummies dressed with each PPE. Two PPE styles were also tested in each position against the PMN mines. To enhance the statistical significance of the test data, three shots were performed for each combination of position, threat and PPE. Table 1 summarizes the conditions of each test setup.

Mine\PPE	Unprotected	PPE 1	PPE 2	PPE 3	PPE 4	PPE 5
100 g	3 K, 3P	3 K, 3 P	3 K, 3 P	3 K, 3 P	3 K, 3 P	3 K, 3 P
200 g	3 K, 3P	3 K, 3 P	3 K, 3 P	3 K, 3 P	3 K, 3 P	3 K, 3 P
PMN	NA	NA	2 K, 2 P	3 K, 3 P	NA	NA

Table 1: Test Matrix (Number of Shots, P=Prone, K=Kneeling).

Post-shot damage assessment was conducted immediately following the shot and initial safety period. The initial damage assessment included photographic documentation; inspection of suit, dummy, and instrumentation; and preliminary evaluation of the acquired data. The dummies were dressed in woven cotton trousers and shirts beneath the PPE to enable detection of fragment penetration. Each piece of PPE was thoroughly examined for tearing, fragment penetration or partial penetration, and overall integrity. Damaged PPE components were replaced as required.

Suits

The five PPE chosen for this test series represent the range of demining protective equipment that are commercially available. PPE 1 has a one piece apron type upper body armor and a visor with a head strap to maintain stability as shown in Figure 3. PPE 2 (Figure 4) consists of a vest type upper body armor with small shoulder wings, groin protection extension, and a visor with head strap that is similar to PPE 1. PPE 3 (Figure 5) has a more elaborate jacket, containing shoulder wings, groin protection extension, and removable ballistic inserts for washing ease, and chaps style trousers for frontal leg protection. The ballistic inserts are located in upper and lower legs, chest, groin, and main body of the suit. PPE 3 also has a lightweight helmet with chinstrap and visor. PPE 4 (Figure 6) has a vest with brachial artery arm guards (shoulder wings), lower area groin guard, and a heavy helmet with chinstrap and visor. PPE 5 (Figure 7) has an elaborate vest, with shoulder wings and groin protector, and shorts for frontal upper leg protection. PPE 5 also has a heavy helmet with chinstrap and a shorter (smaller frontal area) visor. Protective equipment was placed on the dummies as per manufacturers' instructions to ensure consistent placement and provide consistent coverage.

Table 2 lists PPE component weights of the suits and visor projected areas. For blunt trauma protection against mine blasts there is a significant tradeoff between ergonomics and protection. For instance, a larger mass helmet may provide greater protection against blunt force trauma, but may be more difficult to wear. Such tradeoffs underscore the value of a complete assessment of PPE function that includes ergonomics, protection against fragments and protection against blunt trauma.

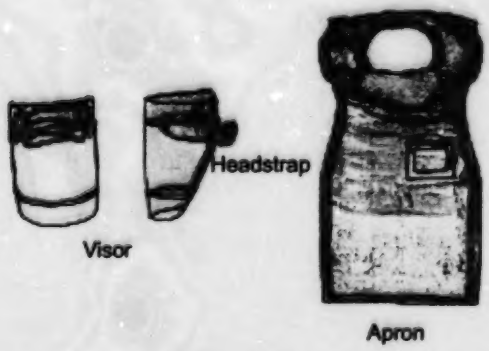

Figure 3: PPE 1

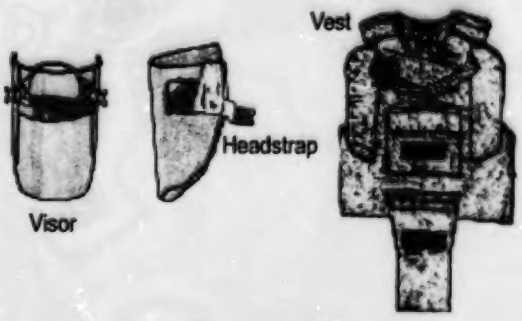

Figure 4: PPE 2

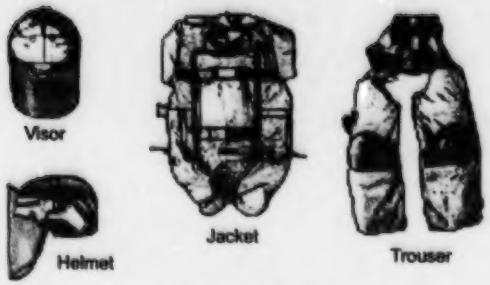

Figure 5: PPE 3

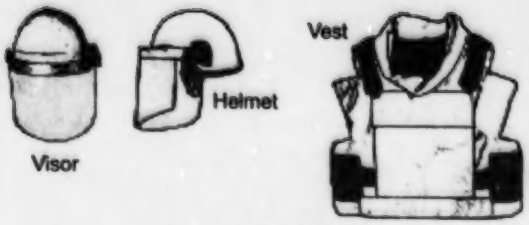

Figure 6: PPE 4

Figure 7: PPE 5

PPE Type	PPE 1	PPE 2	PPE 3	PPE 4	PPE 5
Body Armor Weight (kg)	2.6	3.2	4.1 body 3.6 legs	4.0	4.5 body 1.7 legs
Helmet/Visor Weight (kg)	1.0	0.77	1.3	2.6	2.4
Total Suit Weight (kg)	3.6	4.0	9.0	6.6	8.5
Helmet/Visor Projected Area (cm^2)	632	639	548	677	510

Table 2: Suit Weights and Helmet Projected Area

3. RESULTS

In subsequent sections, the effectiveness of the PPEs in preventing blunt trauma is evaluated relative to the unprotected dummy tests. Head, neck and thoracic blunt trauma are considered.

3.1 Head Trauma

Fatalities from head injuries are very significant in actual mine blasts [Landmine-2000]. These injuries may be caused by mine fragments, environmental debris thrown by the blast, direct blast impingement on the head, or the blast forcing protective headgear into the head. One injury criterion commonly used with the Hybrid III dummy head/neck complex is the Head Impact Criterion (HIC) for concussive head injury [Versace-1971]. HIC includes the effect of head acceleration and duration; when the acceleration is expressed in g's a HIC value of 1000 is specified as the level for onset of severe head injury.

HIC values for the tests using kneeling dummies are presented in Figure 8. As expected, the addition of a PPE helmet to an unprotected dummy improved protection from head trauma for some of the PPE tested. Helmets 4 and 5 performed well for both the 100 g and 200 g simulated mines. The helmet of PPE 3 decreased HIC significantly for the 100g charge only. Similar trends are seen with the PMN mines and the simulated mines.

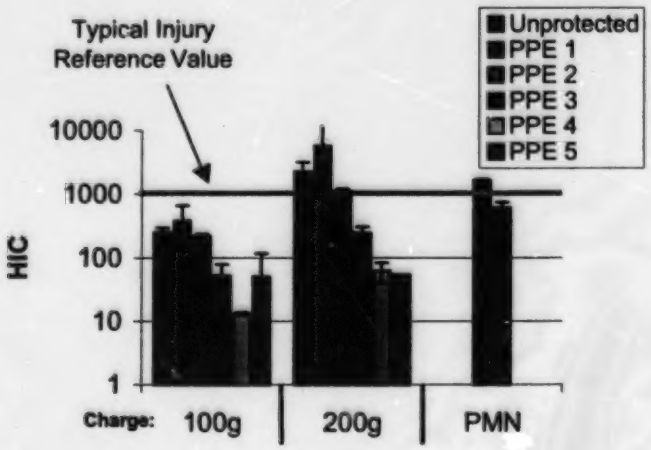

Figure 8: HIC Values for Mine Blast into Kneeling Dummy, All Charge Sizes, All PPEs

Unexpectedly, the facial protection with PPE 1 did not reduce the risk of head blunt trauma when compared to the unprotected case. The physical features of the head protection gear, including the projected frontal area and the mass (Table 2) provide an explanation for the substantial increase in HIC values from the unprotected dummy to a dummy protected by PPE 1.

First, the heavier helmet/visor sets produced lower HIC values. The two heaviest helmets, those from PPE 4 and PPE 5, performed better than those from the other PPE for dummies in the kneeling position because the larger mass decreases the acceleration of the head, resulting in a smaller HIC value. The mass of the standard Hybrid III head/neck complex is 5.8 kg. So, the 2.6 kg mass of the helmet/visor set from PPE 5 adds approximately 45% more weight to the structure, and probably explains the significant drop in HIC when suit 5 armor is added to an unprotected dummy. There is, however, an obvious tradeoff for the protective value of added helmet mass. Increasing the helmet mass without regard for ergonomic factors of wearability and heating may result in limited usage of the face protection. Second, larger frontal areas of the helmet/visor sets tended to increase the risk of head injury from mine blasts. This frontal area dependence arises from the increased exposure to the blast flow, the larger visors can 'catch' more of the blast wave and induce larger head accelerations.

Figure 9 presents the results for dummies in the prone position. Only PPE 5 reduced the HIC for the 200 g charge when compared to the unprotected values. In all other cases HIC was not significantly different. Geometric differences between the prone position and the kneeling position produce this difference in injury risk. The head in the prone position is more upright

than the kneeling, so the blast streams more tangentially to the surface of the visor. This decreases the effect of frontal surface area on the HIC value. However, there is still some evidence of a mass effect as the PPE with larger helmet masses still have lower risk of blunt trauma injury.

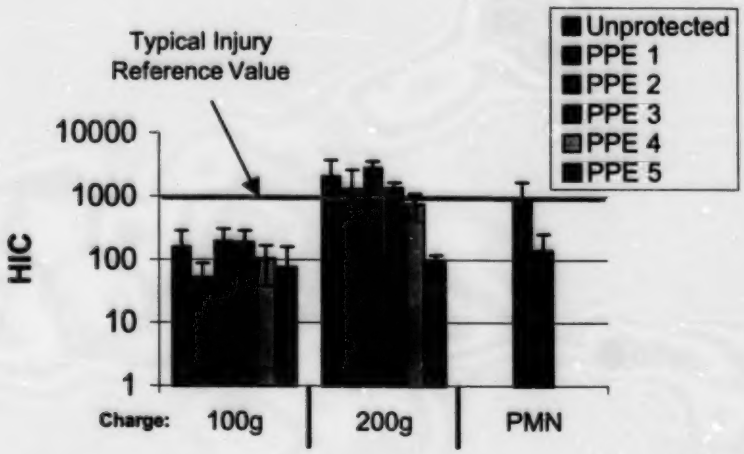

Figure 9: HIC Values for Mine Blast into Prone Dummy, All Charge Sizes, All PPEs.

To further quantify the relationship between the helmet mass, projected frontal area, and HIC, the HIC values were plotted against the helmet parameters and linear curve fits were applied to the data. Four different data sets were considered: kneeling position, 100g charge; kneeling position, 200g charge; prone position, 100g charge; and prone position, 200g charge. Each data set had a separate linear curve fit.

The HIC values were plotted against the nondimensional area/mass (cm^2/kg) ratio for each PPE helmet and the linear curve fits were determined for the four data sets. The average R^2 for these fits varied from 0.08 (P100) to 0.79 (K200). It was easy to distinguish between the 200g and 100g charges on this plot, as the 200g charge data sets (both kneeling and prone) had much large slopes than the 100g charge data sets.

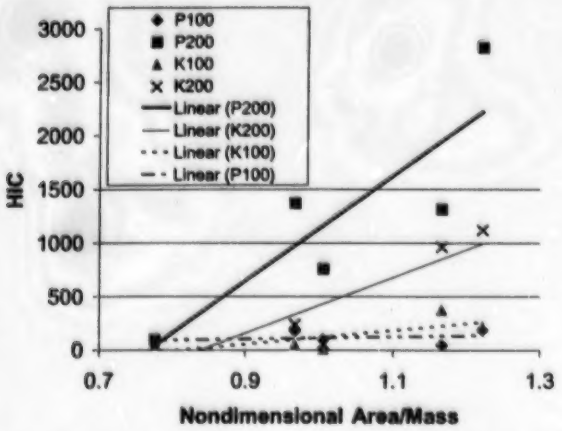

Figure 10: Variation of HIC with Helmet Frontal Area/Helmet Mass for Simulated Mines of 100 g and 200 g (K = Kneeling, P = Prone)

3.2 Neck Trauma

The probability of neck injuries from blasts depends on the different rates of acceleration of the head and of the chest relative to each other. Physical trauma to the neck may be evaluated using the neck force transducers incorporated in the Hybrid III dummy. Barring local damage to the neck itself, the dynamic impulse in the neck must be transmitted through the relative motion of the head and the chest. This transmission of force is relatively slow compared to the duration of the blast wave loading time. So, neck injuries in blast are similar in rate to impact neck injuries that have been studied in automobile safety and other contexts. There is a proposed set of neck injury criteria promulgated by the National Highway Traffic Safety Administration (NHTSA) termed the N_{ij} criteria [Eppinger-2000]. Values of N_{ij} greater than 1.0 correspond to a 22% risk of severe neck injury.

Figure 11 and Figure 12 illustrate the trends in suit performance for the various mine charges in both the kneeling and prone positions. Despite the limited number of reportable tests for the dummy suited with one of the PPEs, it is evident that the average value for N_{ij} for all cases (position and charge) is reduced for the protected dummy. However, some test series did have higher N_{ij} values within the data set than the average baseline unprotected dummy. This is apparent by the variance within the series involving PPE 3 in the prone position with a 100 g charge (Figure 12). Despite sufficient data to significantly support the claim, the potential exists for a lightweight visor only or visor/helmet combination to add enough projected area to the dummy head without substantial counterbalancing mass that the N_{ij} values would actually increase for the protected dummy. However, the highest N_{ij} value reported for all the tests conducted was 0.55, which is well below the 1.0 IRV threshold. With the data resulting in such low N_{ij} values, we can conclude that for this test series, there exists a very small risk of serious (AIS $\geq$ 3) injury.

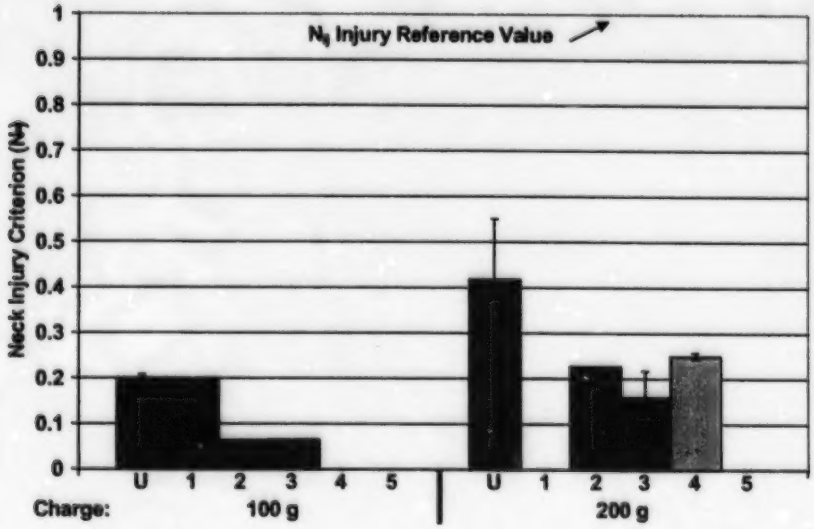

Figure 11: Effect of PPE on neck injury for dummy in the kneeling position.

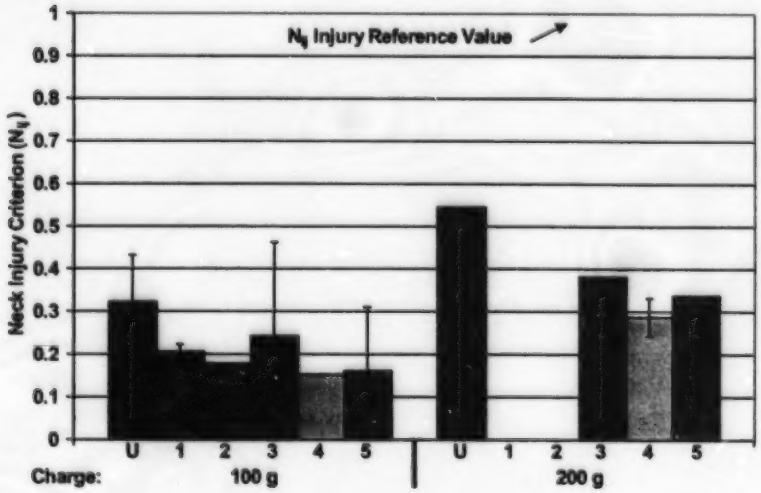

Figure 12: Effects of PPE on neck injury for dummy in the prone position.

Many parameters can influence the effectiveness of the PPEs, including mass, projected area, coverage area, and the position in which they are evaluated. For a larger projected area, a higher momentum transfer from the blast is transmitted to the head. However, the additional mass by the helmet increases the inertial resistance of the head/helmet composite, reducing the acceleration and delaying and reducing the peak force applied. Other variations are a result of the distribution of the projected area of the helmet and faceshield. The higher the projected area is on the head, the farther the resultant force of the blast is from the neck, thus creating a longer moment arm for the loading to act.

3.3 Thoracic Trauma

The blast pressure waves and following pressure wave from the detonation of a mine have the potential to produce severe blunt trauma to a human thorax in proximity to the blast. Several injury criteria have been developed to characterize the risk of thoracic injury. One widely used criterion, based on maximum displacement of the chest wall, allows a maximum 63-mm chest deflection in the 50th percentile male Hybrid III dummy [Eppinger-2000].

The chest injury criteria were initially used to assess the effects of many of the test parameters including the charge size, dummy position, and suits. The peak chest compression for any of the tests was 2.6 mm, which falls significantly below the IRV for chest compression. The majority of tests produced chest compressions below 1 mm, and the average chest compression for all tests was only 0.6 mm. These small values lead to two conclusions for the test analysis. First, there exists a very low risk of chest injury related to compression. Second, the small compression values are so small that the inherent error of the chest slider mechanism may become significant, thus limiting the statistical trends that may be inferred from the data.

The protective equipment was evaluated relative to the unprotected dummy for both the 100g and 200g charge levels and for both the kneeling and prone positions (Figure 13 and Figure 14). As discussed earlier the peak compression values are significantly below accepted IRVs and have the potential to be significantly affected by the compliance in the sensor itself. However, one surprising result is that peak chest displacements for several tests with a suited dummy are higher than those for an unsuited dummy. Therefore it may be concluded that the potential exists that a large profile, low mass thoracic protection suit may actually exacerbate the thoracic loading.

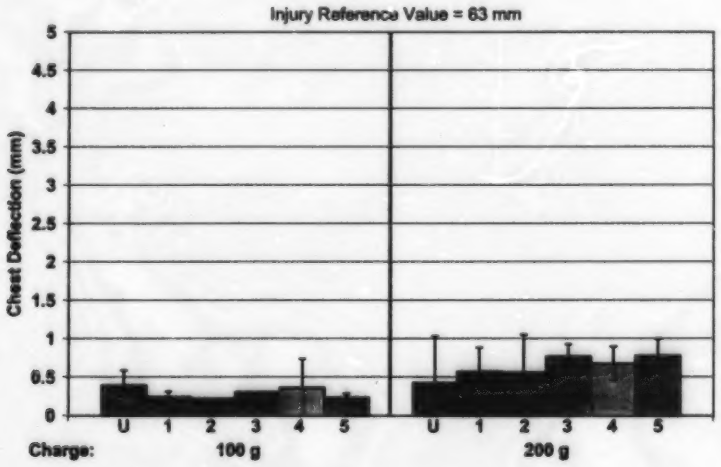

Figure 13: Peak Chest Compression for the Unprotected and Protected Dummy in the Kneeling Position.

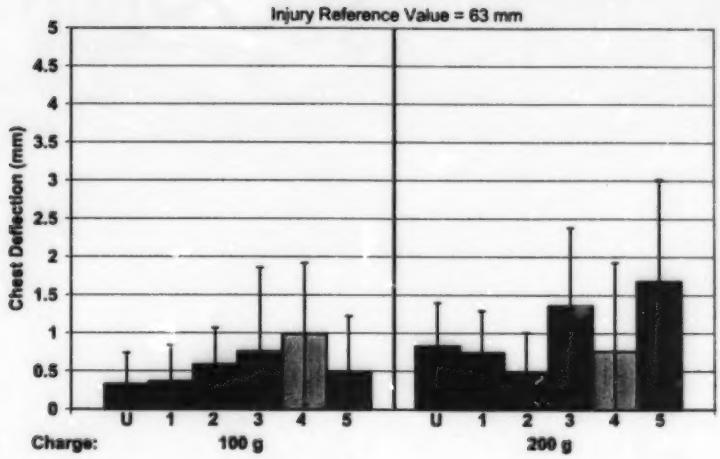

Figure 14: Peak Chest Compression for the Unprotected and Protected Dummy in the Prone Position.

4. CONCLUSIONS

This study evaluated the performance of 5 commercially available PPEs using a recently developed test methodology for evaluating the risk of blunt trauma while wearing PPEs in a demining posture. The PPE's showed some capability for protecting against blunt trauma from mine blasts using standard injury criteria. Paradoxically, however, the dummy head blast response for some of the PPEs increased from the unprotected dummy. This is likely the result of blast interaction with increased surface area of the protection. This result emphasizes the importance of an objective test methodology to evaluate level of blast protection.

Design of personal protective equipment against fragment and blast damage when demining involves numerous tradeoffs between protection of various types and ease of use. Such tradeoffs underscore the value of a complete assessment of PPE function that includes ergonomics, protection against fragments and protection against blunt trauma.

Acknowledgements

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